COMPARISON OF SEISMIC PROVISIONS OF EBCS 8 AND CURRENT MAJOR BUILDING CODES PERTINENT TO THE EQUIVALENT STATIC FORCE ANALYSIS

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ABSTRACT

A comparison of seismic provisions having relevance to the Equivalent Static Force (ESF) method of analysis according to current major building codes worldwide is presented. The codes compared include the latest two editions of the Uniform Building Code (UBC 94 and UBC 97), the International Building Code (IBC 2000), the European Prestandard (Eurocode 8, 1998), and the Ethiopian Building Code Standard (EBCS 8, 1995). The comparison is made on the basis of the specified base shear coefficient, the vertical distribution of the base shear, the story shear and overturning moment, the considerations for torsion, P-delta effect, and the limitations on the story drift. Substantial differences are observed among the codes and even within different editions of a code, a good example being the UBC series. It is also shown that the most recent American codes like UBC 97 and IBC 2000 exhibited drastic changes in the definition of the base shear coefficient and in other pertinent regulations as compared to the classical forms familiar to most users.

INTRODUCTION

The two most common methods of analysis of structures subjected to lateral forces due to seismic action are the equivalent static force and the response spectrum analyses. The response spectrum analysis is a technique directly based on structural dynamics theory. It presupposes a structure modeled by a multi-degree-of-freedom (MDOF) oscillator subjected to an earthquake ground motion represented by a design response spectrum. Its natural periods and modes of vibration characterize the dynamic behavior of the model. This method of structural analysis demands thus knowledge of vibration of structures and earthquake engineering.

In contrast, the equivalent static force analysis (ESF) is a highly simplified technique derived from structural dynamics theory with the aim of rendering it usable to structural engineers without a sufficient background of vibration theory and earthquake engineering. Its applicability is limited to structures satisfying certain conditions of regularity and height limits. The method is based on the dynamics of a single-degree-of-freedom (SDOF) oscillator or an MDOF system vibrating in accordance with a single specified shape. The latter type of oscillator is referred also to as a generalized-single-degree-of-freedom system. The dynamic behavior of such models is characterized by a single natural period. The seismic action can be represented by the same design spectrum also employed in the method of response spectrum analysis described above.

From observations of the analytical relationships developed in the dynamics of generalized SDOF systems, it is possible to establish simple formulas for the natural period, the seismic action and the manner of height-wise distribution of the lateral force. Various other additional factors like site soil, occupancy importance, inelastic ductile response, and the like, which influence the response can also be taken into account by introducing appropriate coefficients into these formulas. However, different degrees of approximations are associated with the specifications of these quantities depending on past performance of structures to earthquake ground motions, local construction practice and the nature of the ground motions. As a result, provisions of various local codes geared to this effect differ from each other and sometimes substantially.

The objective of this paper is to make a comparison of provisions of selected codes having relevance to the ESF method. Various aspects of the ESF method of analysis are used as bases for comparison. These include the form and details of the base shear equation; the distribution of the base shear with height; story shear, moment and torsion; secondary effects due to P-delta; and similar others. Such a comparison is necessary to establish the status of codes with respect to others in common use. It also helps to view codes from the perspective of the state-of-the-art. For these reasons, such works can not be considered as a one-time job.

A total of five different codes are compared: the last two editions of the Uniform Building Code [1,3]*; the most recent 2000 International Building Code [4]; the Eurocode Prestandard – Eurocode 8, 1998 [6]; and the Ethiopian Building Code Standard [7]. The comparison made on the basis of the criteria mentioned above revealed as expected that no code is fully identical to any other. Some provisions of a code are shared by others, and other provisions are unique to that code. The observations made in the provisions of EBCS 8 are also no exceptions.

A similar work that compares provisions pertinent to the response spectrum method of analysis is planned for the near future. It is hoped that such works will play a role to initiate updating of provisions of local codes, particularly EBCS 8.

THE UNIFORM BUILDING CODE (UBC) SERIES

The UBC seismic regulations are generally based on the series of publication of the Structural Engineers Association of California (SEAOC) released regularly since 1959, commonly known as the SEAOC Blue Book.

With respect to provisions pertinent to the equivalent static force analysis (ESF), particularly with regard to the basic form of the base shear formula, drastic changes were introduced in UBC 88 and UBC 97. In UBC 88, the formula $C_s = ZIC/R_w$ for the base shear coefficient replaced the older version of $C_s = ZIKCS$. Recently, UBC 97 introduced once again a new approach including a significant change in the expression for the base shear coefficient that took the form of $C_s = C_v I/RT$. The details of the last two forms and other pertinent provisions and requirements will be discussed in the following sections on the basis of the 1994 and 1997 releases of the UBC.

* The outdated UBC 94 is included for two reasons:
(a) because the new forms of the base shear formula specified by UBC 97 and IBC 2000 are not expected to be familiar to most potential readers and explanation of them is easier if reference is made to such older and familiar versions; and
(b) because important similarities exist between provisions of EBCS 8 and this code.

UBC 94

The UBC 94 seismic regulations are based on the 1990 SEAOC Blue Book – Recommended Lateral Force Requirements and Tentative Commentary which in turn was partly based on the provisions of the Applied Technology Council recommendations (ATC-06-1978) and of the Building Seismic Safety Council guidelines (BSSC-1994) [1,9].

UBC 94 allows the use of the ESF method to all regular structures not taller than 73m and to all irregular structures not exceeding 5 stories or 20m in height irrespective of the seismic zone. Based on the seismic zoning described below, it also allows the ESF method for all structures in Zone 1 and all common-occupancy structures in Zone 2.

Base Shear

The total base shear is specified as

$$V = \left(ZIC/R_w\right)W \qquad (1)$$

Where Z is the seismic zone factor, I the importance factor, C the site coefficient, R_w the structural system coefficient, and W is the total seismic weight of the structure.

The Seismic Zone Factor, *Z*

This factor represents the seismicity zone of the site in the USA and assumes one of the values of 0.075, 0.15, 0.20, 0.30, or 0.40.

The Importance Factor, *I*

This factor is introduced to increase the base shear for essential and hazardous facilities by assigning the maximum value of I=1.25 while all other structures are assigned I=1.0. It is worth mentioning that the maximum value of I was 1.50 according to previous versions of the Code like UBC 85 [2].

The Site Coefficient, *C*

This coefficient is specified by

$$C = 1.25S/T^{2/3} \leq 2.75 \qquad (2)$$

where S is the site coefficient and T is the fundamental period of the structure. The ratio C/R_w is limited to a minimum value of 0.075, which has the effect of setting a minimum value of base shear force for long-period structures.

The Building Period, *T*

The Code specifies two methods for the computation of the period, T.

Method A: This method is based on the empirical formula of

$$T = C_t h_n^{3/4} \tag{3}$$

in which h_n is the height in meters to the top-most floor from the base and C_t assumes one of the values of 0.085, 0.073 or 0.049 for steel moment frames, reinforced concrete frames and eccentrically braced frames, or other structures, respectively.

Method B: As an alternative, the Code provides Rayleigh's formula given by:

$$T = 2\pi \sqrt{\sum_{i=1}^{N} W_i \delta_i^2 \Big/ g \sum_{i=1}^{N} f_i \delta_i} \tag{4}$$

where f_i represents a reasonable force distribution consistent with the vertical distribution of the base shear yet to be determined; δ_i are the elastic lateral deflections due to f_i.

The empirical formulas given in the previous versions of UBC, like UBC 85, based on the number of stories of the building and its dimensions are no more provided even as alternatives in this edition. Besides this, Rayleigh's closed form relation, Eq. (4), is provided that has a good theoretical background in structural dynamics.

The Site Coefficient, S

With the purpose of accounting for site soil amplification of the ground motion this coefficient assumes one of the values of 1.0, 1.2, 1.5 or 2.0 depending on the four site soil classes provided on the basis of qualitative categorization. This coefficient is no longer specified based on the period ratio of the structure to the soil, as was the case in, for example, UBC 85.

Structural System Coefficient, R_w

This factor serves the purpose of accounting for structural ductility, and its values range between 4 and 12 depending on the given detailed description of different possible structural systems.

For a common occupancy structure (I=1), with an elastic response (R_w=1) and a base shear coefficient normalized with respect to the zone factor, the base shear coefficient simplifies to the expression in Eq.(2). The plots of this equation for the four different soil classes are shown in Fig. 1. It is important to note that the spectra for all soil classes are bounded by 2.75 at the top and decline according to $T^{-2/3}$ with increasing period.

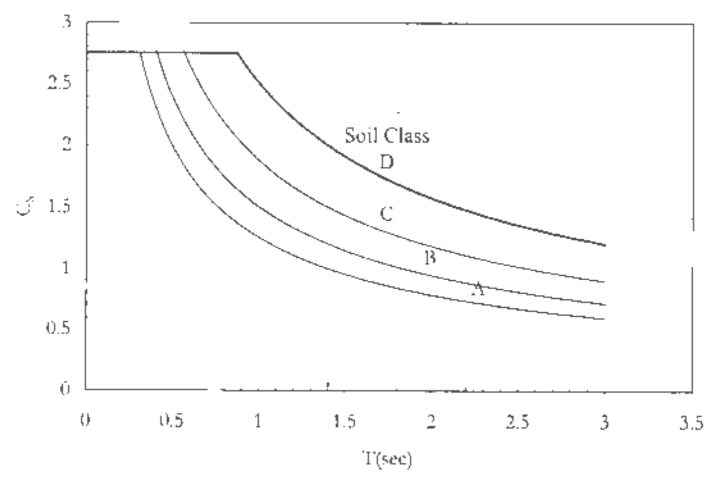

Figure 1 The design spectra of UBC 94 for I=1, R_w=1 and a base shear coefficient normalized with respect to the zone factor

Vertical Distribution of Base Shear

The base shear determined in Eq. (1) is distributed vertically in accordance with:

$$F_x = (V - F_t)\left(W_x h_x \Big/ \sum_{i=1}^{N} W_i h_i\right) \quad (5)$$

where the top force, F_t, is given by

$$\begin{aligned} T \le 0.7\,\text{sec}: \quad & F_t = 0 \\ T > 0.7\,\text{sec}: \quad & F_t = 0.07TV \le 0.25V \end{aligned} \quad (6)$$

W and h are the weight at and the height from the base to a particular floor level.

Story Shear and Story Overturning Moment

The shear force, V_x, and the overturning moment, M_x, at any particular story are found as the sum of all lateral forces above and their moment about that story, respectively. Thus

$$V_x = F_t + \sum_{i=x}^{N} F_i \quad (7)$$

and

$$M_x = F_t(h_n - h_x) + \sum_{i=x}^{N} F_i(h_i - h_x) \quad (8)$$

Torsion

Where diaphragms are not flexible, the Code requires considering an accidental torsion equal to the story shear times ±5% of the floor plan dimension in the perpendicular direction. This is in addition to the calculated torsion due to the eccentricity between the mass and stiffness centers of the story.

If torsional irregularity exists, the accidental torsion is increased by the factor

$$A = \left(\frac{\delta_{max}}{1.2\delta_{avg}}\right)^2 \le 3.0, \quad (9)$$

in which

δ_{max} maximum displacement at Level x;

δ_{avg} = the average displacement at the extreme points of the structure at Level x.

P-Δ Effect

It is required that the P-delta effect be considered in the determination of member forces and story displacements, if this is found significant. The P-delta effect need not be considered if the ratio, θ, of the secondary to the primary moment for any story does not exceed 0.10, or in Seismic Zone 3 and 4, where the story drift ratio, Δ/h, does not exceed $0.02/R_w$. The ratio, θ, is defined by

$$\theta = (P_x\Delta)/(V_x h) \quad (10)$$

where

P_x = total dead, floor live and snow load above the story;

Δ = the story drift;

V_x = the story shear;

h = the story height.

Story Drift, Δ:

The story drift is limited in accordance with the following:

$$\begin{aligned} For\,h_n < 20m: \; & \Delta \le 0.04h/R_w \; and\,\Delta \le 0.005h \\ For\,h_n \ge 20m: \; & \Delta \le 0.03h/R_w \; and\,\Delta \le 0.004h \end{aligned} \quad (11)$$

where h_n is the building height. The displacement includes both the translational and rotational components. The displacement due to P-delta effect must also be included if found significant as explained above. The forces employed for the calculation of the drift are not, however, subject to the upper bound limitation on the vibration period as in the computation of C.

UBC 97

The seismic regulations of UBC 97 are based on the recommendations of the 1994 SEAOC Blue Book [3]. The Code provides for both the ESF and dynamic methods of analysis procedures as before. It represents, however, a dramatic change in its regulations of particularly the lateral forces as compared to the previous editions.

Base Shear

The base shear, V, is specified by

$$V = C_s W \quad (12)$$

where the seismic base shear coefficient, C_s, is given by

$$0.11C_aI \le C_s = (C_vI)/(RT) \le (2.5C_aI)/R \quad (13)$$

In Eq. (13), C_a and C_v are the seismic coefficients; I is the importance factor; T is the period of the structure; R is the seismic force reduction factor; and W is the total seismic weight of the structure.

As shown in Eq. (13), the base shear coefficient is bounded both at the top and bottom. It is also limited to another minimum value for the most seismic zone to account for near-source effects.

The form of the seismic coefficient in Eq. (13) is significantly different from those used in the previous editions of the Code as can also be compared with Eq. (1). The details involved in the various factors reflect also a major deviation from the corresponding ones used in the past. These factors are discussed in the following sections.

The Seismic Coefficients, C_v and C_a

Probably, the most significant change introduced by UBC 97 is the introduction of the seismic coefficients. These coefficients account both for the seismicity of the site and the soil effect and are thus given for the different seismic zones and soil profile types. The seismic zones and the corresponding factors assigned are essentially the same as those employed in UBC 94. However, unlike the four soil categories used in UBC 94, this new edition defines six different types of soil profiles identified by the symbols S_A to S_F.

Furthermore, the definitions are based not only on qualitative description of the profile, but also quantitatively on the basis of the weighted magnitude of the shear wave velocity, blow counts of Standard Penetration Test, and undrained shear strength of the layers forming the profile. A detailed procedure is also provided for determining the soil profile type. This is a significant progress in an attempt to rationally consider one major influence[1] of the soil on seismic forces in structures.

[1] Though detailed a procedure, it does not attempt to take into account soil structure interaction - the other major factor that can significantly influence the seismic response of the structure.

While C_v=C_a for soil profiles S_A (hard rock) and S_B (rock), the factor C_a is consistently less than C_v for the remaining soil profile types.

Seismic Importance Factor, *I*

This factor assumes the value of 1.0 for common-occupancy buildings and 1.25 for essential and hazardous facilities similar to UBC 94. However, the descriptions of the facilities in UBC 97 are much more detailed.

Period of the Structure, *T*

The same two methods - Method A and Method B– specified by UBC 94 are also specified here. In addition to this, UBC 97 provides an alternative empirical formula for the computation of C_t of Eq.(3) for structures with concrete and masonry shear walls. The same limitations as in UBC 94 are also imposed on the values of T computed from Method B.

Seismic Force Reduction Factor, *R*

This factor represents, according to the code, the inherent *overstrength* and *global ductility capacity* of the lateral force resisting systems. It corresponds to the Structural System Coefficient, R_w, of UBC 94, but assumes values in the range of 2.2 to 8.5 unlike R_w, which may take values ranging from 4 to 12.

It is important to note that the concept of overstrength is newly introduced in this code and the range of values of R is narrowed down and lowered. It seems also that this factor R of UBC 97 can be split into two components that account for overstrength and ductile inelastic response.

For a common occupancy structure (I=1), with an elastic response (R=1) and the base shear coefficient normalized with respect to the zero-period spectrum, C_a [3], the plots for the five different soil classes, S_A to S_E, of Zone 3 are shown in Fig. 2. It is important to note that a general set of plots for all zones could not be made as was possible in UBC 94 (compare with Fig. 1). However, as the trend is similar, the plots of Fig. 2 can be taken as representative curves for the purpose of this paper. The detailed procedure followed in the preparation of the curves is omitted.

For Soil Class S_F, site-specific dynamic response analysis with site-specific geotechnical study is required.

of Eq. (12) and its vertical distribution without the lower bound limitations imposed on the base shear and the upper bound limitation on the period.

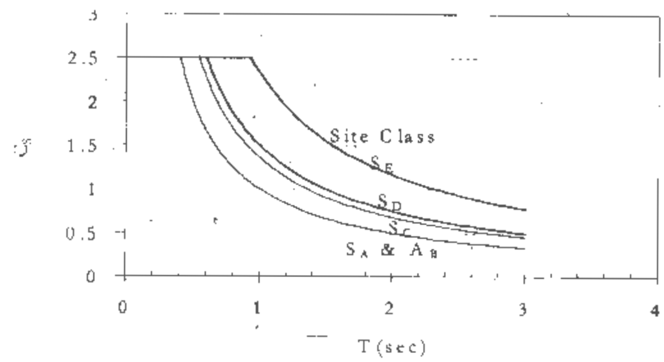

Figure 2 Design Spectra of UBC 97 for the different soil classes normalized with respect to C_a

It is noteworthy that the upper bound of the spectra in this edition of UBC is lowered from 2.75 to 2.50 and the declining branches vary according to T^1 instead of $T^{2/3}$.

Lateral Force Distribution, Story Shear and Story Overtuning Moments

There is no change in the procedure of computation of these quantities from those of UBC 94.

Torsion and P-delta Effects

Essentially the same requirements are made in both editions of the Code.

Story Drift Limitations

The story drift limitations of UBC 97 exhibit significant differences from those in its predecessor both in form and content. The maximum inelastic response displacement, Δ_m, is limited in accordance with

$$\begin{aligned} &For\ T < 0.7 : \Delta_m \leq 0.025h; \\ &For\ T \geq 0.7 : \Delta_m < 0.020h. \end{aligned} \quad (14)$$

where Δ_m is computed from

$$\Delta_m = 0.7R\Delta_s \quad (15)$$

Δ_s is the design level response displacement determined on the basis of the design seismic force

THE INTERNATIONAL BUILDING CODE, IBC 2000

The International Building Code – IBC 2000 has been published by the International Code Council (ICC) in cooperation with the three major US code writing authorities – BOCA, ICBO and SBCCI[2] – with the intention of establishing uniform regulations for building systems consistent with and inclusive of the existing model codes in the US [4].

The seismic regulations of IBC 2000 are based on the 1997 edition of NEHRP[3] – Recommended Provisions for Seismic Regulations for New Buildings and Other Structures [5]. The provisions relevant to the ESF method of analysis are presented in the following sections.

Base Shear

The seismic base shear, V, in a given direction is determined from the familiar expression

$$V = C_s W \quad (16)$$

where C_s is defined as the seismic response coefficient and W as the effective seismic weight. The seismic response coefficient, C_s, is given by

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[2] BOCA: Building Officials and Code Administrators
ICBO: International Conference of Building Officials
SBCCI: Southern Building Code Congress International
[3] NEHRP: National Earthquake Hazard Reduction Program

$$C_s = \frac{S_{D1}}{(R/I_E)T} \quad (17)$$

It is bounded both at the top and bottom according to the following:

$$0.044\, S_{DS} I_E \le C_s \le \frac{S_{DS}}{(R/I_E)} \quad (18)$$

In Eq. (17) and (18),

- S_{DS} = the design spectral response acceleration at short period;
- S_{D1} = the design spectral response acceleration at one-second period;
- I_E = the seismic occupancy importance factor;
- T = the fundamental period of the building; and
- R = the response modification factor.

The total base shear, V, is also limited to another minimum value for buildings of specified categories. The various factors in Eq. (17) and (18) are discussed in the following sections.

The Design Spectral Acceleration Parameters, S_{DS} and S_{D1}

The 5%-damped design spectral response acceleration at short periods, S_{DS}, and at one-second period, S_{D1}, are specified as

$$S_{DS} = \frac{2}{3} S_{MS} \quad and \quad S_{D1} = \frac{2}{3} S_{M1} \quad (19)$$

where S_{MS} and S_{M1} are defined as the maximum considered earthquake spectral response accelerations for short period and one-second period, respectively. These quantities are in turn given by

$$S_{MS} = F_a S_S \quad and \quad S_{M1} = F_v S_1 \quad (20)$$

The quantities in Eq. (20) are

F_a and F_v: site coefficients;
S_s and S_1: the 5% damped maximum considered earthquake mapped spectral accelerations for short period and one-second period structures on Site Class B.

The site Coefficients, F_a and F_v

The subscripts a and v on the site coefficients, F_a and F_v, seemingly indicate the free ground acceleration and velocity that are amplified most by the structure in the short and long period ranges, respectively. Values of F_a and F_v are provided in a tabular form as functions of the Site Class and the 5%-damped mapped spectral response accelerations, S_s and S_1.

The latter are provided in form of contoured maps for the whole of the US to a significant detail. It is thus important to note that this marks a milestone in the definition of the base shear coefficient for ESF method of analysis: from the classical peak ground acceleration-based definition to this new acceleration response spectrum-based definition.

Six different site classes ranging from Site Class A to F are defined. For Site Class A (hard rock) and Site Class B (rock) both site coefficients are equal assuming the value of 1.0 and 0.80, respectively, irrespective of the mapped spectra, S_s and S_1. The values of F_a and F_v consistently increase starting from the above values with the site class tending from B (rock) to E (soft soil profile) for a specified S_s or S_1. These quantities decrease, however, consistently with increasing values of S_s or S_1 for a given site class between C and E. No specific values of F_a and F_v are assigned to Site Class F for all values of S_s and S_1. Rather, site-specific geotechnical investigation and dynamic site response analyses are required for this site class.

A detailed procedure similar to that given by UBC 97 is also provided by IBC 2000 for site classification on the basis of shear wave velocity, standard penetration test blow-count, and undrained shear strength of the layers forming the soil profile of a site.

The Seismic Occupancy Importance Factor, I_E

This factor assumes one of the values of 1.0, 1.25 or 1.50 depending on the occupancy nature. The maximum value of 1.50 is an evident deviation from the UBC 97 requirements, in which this large value was dropped.

The Fundamental Period, T

IBC 2000 requires that T be established with the help of a properly substantiated analysis using the structural properties and deformational characteristics of the resisting elements. As an alternative, it also provides the approximate formula of Eq. (3) given by both UBC 94 and UBC 97.

The Code provides also an additional formula for concrete and steel-moment resisting frame buildings not exceeding 12 stories in height and with a minimum story height of 3m. This latter formula is given by

$$T_a = 0.1N \tag{21}$$

where N is the number of stories and T_a is the approximate period. It is to be noted that this formula was provided by earlier editions of UBC, for example UBC 85, as an alternative, but for all building types.

The Code requires that the period, T, calculated on the basis of properly substantiated analysis methods be limited in accordance with

$$T \leq c_u T_a \tag{22}$$

where c_u is referred to as the coefficient for upper limit on calculated period and provided by the Code as a function of S_{D1}. The values of c_u increase from 1.2 to 1.7 with decreasing values of S_{D1}. This requirement deviates once again from that of UBC 97.

The Response Modification Factor, *R*

This factor varies from 1.25 for inverted pendulum structures with ordinary steel moment frames to 8 for some moment resisting frames and dual systems. The details in the description of the different structural systems and the allocation of values of R are more exhaustive in this code than in any of the UBC series.

It can be shown that R can be expressed as the product of two factors: a ductility reduction factor, R_d, and a structural overstrength factor, Ω_0. This trend of splitting the response modification factor into R_d and Ω_0 is inherent in the code but not explicitly stated. It seems that the approach of UBC 97 that provides only global values of the factor, R, instead of separate values of R_d and Ω_0, is preferred until seemingly further research shades better light on the issue.

For a common occupancy structure (I_E=1), with an elastic response (R=1) and the base shear coefficient normalized with respect to the zero-period spectrum of $0.4S_{DS}$ [4], the plots for the five different soil classes, A to E, for sites with spectral accelerations of S_1=0.3 and S_S=0.75 are identical to those shown in Fig. 2. It is important to note here also that a single general set of plots representative of all sites could not be made as was possible in UBC 94. The curves in Fig. 2 can, however, be taken as representative.

Vertical Distribution of Seismic Forces

The base shear determined using Eq. (16) is to be distributed vertically in accordance with

$$F_x = V\left(W_x h_x^k \Big/ \sum_{i=1}^{n} W_i h_i^k\right) \tag{23}$$

In Eq. (23), k is a distribution exponent related to the building period. For T≤0.5 sec. k assumes the value of 1, for T≥2.5 it is assigned the value of 2, and for intermediate periods k is found by linear interpolation or may be simply assigned the value of 2.

Equation (23) clearly deviates from the corresponding specification of UBC in any of its editions, which bases the distribution on a linear fundamental mode, while Eq. (23) envisages also a parabolic and other nonlinear mode shapes for long- and intermediate-period buildings. This provision of IBC is of course closer to the reality as it is known that the fundamental mode deviates from linear shape with increasing period. It is also worth noting that the top force, F_t, is no more deducted from the base shear.

Story Shear

The seismic design shear is to be distributed to the vertical elements of the lateral force resisting system on the basis of the diaphragm rigidity. For rigid diaphragms defined in the Code, the distribution is made in accordance with the relative lateral stiffness of the vertical resisting elements and the diaphragm. For flexible diaphragms defined also in the Code, the distribution is made on the basis of the tributary area of the diaphragm to each line of resistance.

Story Overturning Moment

The overturning moment, M_x, at any level, x, is determined from

$$M_x = \tau \sum_{i=x}^{N} F_i\left(h_i - h_x\right) \qquad (24)$$

The various terms in Eq. (24) are as defined earlier, except the overturning moment reduction factor, τ. This factor assumes the value of 1.0 for the top 10 stories, 0.8 for the 20th story from the top and below, and an intermediate value obtained by linear interpolation for the stories between the 10th and 20th story from the top.

This concept of reducing the story overturning moment for lower stories of high-rise buildings is once again a new approach presumably introduced to account for the flexibility of the structure that can exhibit reversal of force direction. It is implied that the reduction is not made for 10-story and shorter buildings.

Torsion

Where diaphragms are not flexible, the sum of the actual torsion, M_t, and the accidental torsion, M_{at}, is considered in the distribution of the story shear. The accidental torsion is based on the ±5% eccentricity specified also by UBC.

For structures exhibiting torsional irregularities, the effects are accounted for by multiplying the sum of M_t and M_{at} by the same factor given in Eq. (9), unlike in UBC 94 and 97, where this factor is applied only on the accidental torsion, M_{at}. The deviation from the corresponding UBC requirement is once again evident.

Story Drift Determination and Limitations

The design story drift, Δ, is generally computed as the difference of the deflections at the center of mass at the top and bottom of the story under consideration.

The deflection, δ_x, of Level, x, is determined from

$$\delta_x = \frac{C_d \delta_{xe}}{I_E} \qquad (25)$$

where

δ_{xe} = the deflection determined from the elastic structural analysis without the upper bound limitations of Eq. (22) imposed on the period, T.

C_d = the deflection amplification factor ranging from 1.25 to 6.5 provided in the same manner as response modification factor, R_w.

I_E = is the occupancy importance factor.

The design story drift is limited to the allowable story drift, Δ_a, for any story, which is provided as a fraction of the story height, h_{sx}, based on the building type and seismic use group. Accordingly, Δ_a ranges from $0.007h_{sx}$ to $0.025h_{sx}$. For common reinforced concrete and steel structures taller than four stories, Δ_a takes one of $0.010h_{sx}$, $0.015h_{sx}$ or $0.020h_{sx}$ depending on the seismic group. For masonry shear wall and masonry wall-frame buildings, Δ_a takes generally smaller values.

Consideration of *P*-delta Effects

The significance of the *P*-delta is measured by the stability coefficient, θ, defined in a slightly modified form than Eq. (10) as

$$\theta = \left(P_x \Delta\right) / \left(V_x h_{sx} C_d\right) \qquad (26)$$

where P_x is defined as the total unfactored vertical design load at and above Level x; V_x is the story shear force; and the remaining terms are as defined earlier. The secondary effects of the *P*-delta need not be considered if θ does not exceed 0.10 as is also allowed by UBC 94 and 97.

The stability coefficient is also bounded on the top by

$$\theta_{max} = 1/\left(2\beta C_d\right) \leq 0.25 \qquad (27)$$

in which β is the ratio of the shear demand to the shear capacity for the story. A value of 1.0 is allowed if this ratio is not calculated. Eq. (27) is once again a new addition by IBC 2000 towards considering the effects of *P*-delta.

If the computed value of θ is between 0.10 and θ_{max}, the *P*-delta effect is included in the determination of the interstory drifts and element forces. In order to account for the *P*-delta effect on the story drift, for example, the design story drift is increased by the factor $a_d = 1/(1-\theta)$. If θ is greater than θ_{max}, the structure is potentially unstable and needs redesigning. This latter important precautionary note is not explicitly stated in any version of the UBC series.

THE EUROPEAN PRESTANDARD, EUROCODE 8 – 1998

The European Committee for Standardization published this and other pertinent documents in 1994. Eurocode 8 deals with the design and construction of buildings and other works in seismic regions of Europe [6].

This volume stipulates two basic types of analysis, the choice of which depends on the structural characteristics of the building to be analyzed. Of these, the Simplified Modal Response Spectrum Analysis can be interpreted as the Equivalent Static Force (ESF) method. It is supposed to be applied to buildings that can be analyzed by two planar models and whose response is not significantly affected by contributions of higher modes. The important features of this method are briefly presented below in comparison with pertinent regulations of the UBC and IBC discussed earlier.

Base Shear

The seismic base shear is given by the equation

$$V = S_d\left(T_1\right)W \tag{28}$$

In Eq. (28), $S_d(T_1)$ is the ordinate of the design spectrum at the fundamental period, T_1, given by the following equation for the important period range:

$$\begin{aligned}
0 \le T_1 \le T_B: &\quad S_d\left(T_1\right) = \alpha S\left[1+\frac{T_1}{T_B}\left(\frac{\beta_0}{q}-1\right)\right] \\
T_B \le T_1 \le T_C: &\quad S_d\left(T\right) = \alpha S\frac{\beta_0}{q} \\
T_C \le T_1 \le T_D: &\quad S_d\left(T_1\right) = \alpha S\frac{\beta_0}{q}\left(\frac{T_C}{T_1}\right)^{\frac{2}{3}} \ge 0.20\alpha
\end{aligned} \tag{29}$$

In Equation (29), α is the design ground acceleration ratio; S is the soil parameter; β_0 is the spectral acceleration amplification factor for 5% damping; q is the behavior factor; T_B and T_C are limits of the constant acceleration branch and T_D is the beginning of the constant displacement branch of the design spectrum. The values of these parameters are provided for 50% probability of exceedance of the spectral ordinates over the whole period range.

It is to be observed that all branches of the design spectrum are dependent on the soil parameter, S. This is in contrast to the design spectra of many other codes, where the spectra are all limited to a single constant value in the constant acceleration region (Compare Figure 3 with Figures 1 and 2).

The Design Ground Acceleration Ratio, α

This is the ratio of the design ground acceleration, a_g, to the gravitational acceleration, g. The Code envisages that the National Authorities of Europe would be subdivided into seismic zones depending on the local hazard. The hazard within each zone is assumed to be constant and described by the single parameter, a_g, in rock or firm soil. This design ground acceleration corresponds to a reference return period of 475 years and, to which is assigned an importance factor of one.

The Soil Parameter, S

The soil parameter is assigned different values for the three different subsoil classes, A, B, and C, described in the code. The parameter takes the value of 1.0 for Classes A and B and 0.9 for Class C. This trend of assigning a smaller amplification factor for softer and thicker deposits deviates apparently from the corresponding provisions of other codes.

It is important to note that the three soil classes are too few to appropriately cover the different nature of soil profile that could be encountered in reality. Besides, the code does not have provisions for classifying soil profiles on the basis of quantitative measures like SPT blow counts and undrained shear strength.

The Period Limits

The period limits, T_B and T_C, of the constant acceleration branch and, T_D, of the constant displacement branch of the design spectrum are provided for the three different soil classes. For Soil Class A, they assume 0.10, 0.40 and 3.0 sec; for Soil Class B, they take 0.15, 0.60 and 3.0 sec; for Soil Class C, they are assigned 0.20, 0.80 and 3.0 sec, respectively.

The Spectral Acceleration Amplification Factor, β_0

This factor is assigned the constant value of 2.5 for all soil classes and over the whole period range. Its purpose is to account for the amplification potential of the free ground motion by the site soil.

The Behavior Factor, q

This factor accounts for the energy dissipation capacity of the structure mainly through ductile behavior. The factor is an approximation of the ratio of the seismic forces that the structure would experience if its response were completely elastic with 5% damping to the minimum design forces. Its values are given for various materials, structural systems and different ductility levels. For example, for concrete structures q_0 varies from 2.0 for inverted pendulum system to 5.0 for framed and dual systems.

The Building Fundamental Period, T_1

Eurocode 8 allows the use of approximate expressions based on structural dynamics citing Rayleigh method as an example, but without providing the formula. It specifies other empirical expressions instead, but for preliminary design purposes. These expressions are Eq. (3) specified also by UBC 94 and the formula given below:

$$T_1 = 2\sqrt{d} \tag{30}$$

where d is the lateral displacement in meters of the top of the building due to the gravity loads applied horizontally to yield T_1 in seconds.

For a design ground acceleration ratio, $\alpha = 1$, and an elastic response of the structure (q=1), the design spectra of Eq. (29) for the three different subsoil classes are presented in Fig. 3. The reduced upper bound for Subsoil Class C is noteworthy in comparison to Figures 1 and 2 of UBC and IBC. The variation of the spectra in the declining branch is also according to $T^{2/3}$ in contrast to T^1 of UBC 97 and IBC 2000.

Vertical Distribution of Seismic Forces

For the distribution of the base shear, the use of the fundamental mode shape is allowed that is obtained by employing the methods of structural dynamics. The use of an approximate linear mode is also permitted, in which case the distribution is given by Eq. (5) with F_t set to zero. Rigid floors are then assumed in the distribution of the lateral forces so obtained to the lateral force resisting elements of each story.

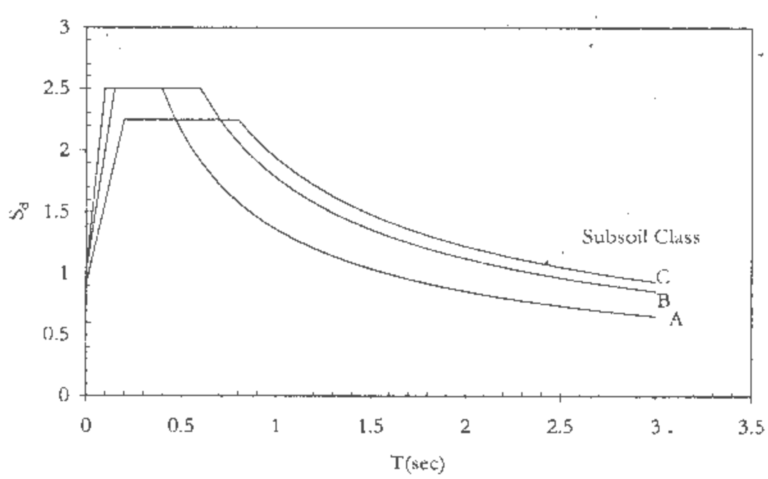

Figure 3 The design spectra of Eurocode 8 for the ESF method of analysis for a design ground acceleration ratio, $\alpha = 1$, and an elastic response of the structure (q=1)

Torsion

An accidental torsion of 5% is considered as in UBC and IBC. In case of symmetric distribution of lateral stiffness and mass, the Code allows for an alternative approach of accounting for accidental torsion, in which the action effects in the individual lateral load resisting elements are amplified by the following factor:

$$\delta = 1 + 0.6x/L_e \tag{31}$$

where x is the element distance from the building center, and L_e is the distance between the outermost lateral load resisting elements. Equation (31) is uncommon in UBC and IBC provisions, and its background is little known.

In structures with torsional irregularities, the code specifies the amplification of the accidental eccentricity by the factor A of Eq. (9) similar to the UBC specification.

Story Drift

The story drift limitations to be observed are $d_r \leq 0.004\mu h$ for buildings having nonstructural elements of brittle materials attached to the structure and $d_r \leq 0.006\mu h$ for buildings having nonstructural elements fixed in a way as not to interfere with structural deformations. In these requirements, h is the story height and μ is a reduction factor that takes into account the lower return period of the seismic event associated with the serviceability limit state. The reduction factor, μ, assumes the value of either 2.0 or 2.5 depending on the importance category.

***P*-delta Effects**

The Code measures the P-delta influence by the moment ratio, θ, defined in Eq. (10) as in UBC 94 and 97. It requires the consideration of the P-delta effects if θ is between 0.1 and 0.2 by increasing the relevant seismic action effects by the factor1 $(1-\theta)$. The P-delta effects need not be considered if θ is less than 0.1. On the other hand, θ is not allowed to exceed 0.3, but without explicitly stating what is to be done if θ exceeds this upper limit.

THE ETHIOPIAN BUILDING CODE STANDARD (EBCS 8 –1995)

EBCS 8 – 1995 is the most recent code standard in Ethiopia dealing with seismic regulations. It is an independent volume covering topics ranging from general requirements on structural analysis and design to specific design provisions for concrete, steel and timber buildings [7]. The general regulations pertinent to the ESF method of analysis are discussed in the following sections.

Base Shear

The base shear for each main direction is determined by the same equation as that of Eurocode 8 given by Eq. (28). The coefficient $S_d(T_1)$ in this equation is, however, given in a different manner as given by:

$$S_e(T) = \alpha\beta\gamma \tag{32}$$

This coefficient is the ordinate of the design spectrum normalized with respect to the gravitational acceleration, g. The three parameters in Eq. (32) are briefly discussed below.

The Design Bedrock Acceleration Ratio, α

This parameter is the ratio of the design bedrock acceleration to the gravitational acceleration and is given by

$$\alpha = \alpha_0 I \tag{33}$$

In Eq. (33), α_0 is the bedrock acceleration ratio for the site that depends on four seismic zones provided. It assumes one of the values of 0.10, 0.07, 0.05 or 0.03. I is the importance factor, that takes one of the values of 1.4, 1.2, 1.0 or 0.8.

The Design Response Factor, β

This factor is given by

$$\beta = 1.2S/T_1^{2/3} \leq 2.5 \tag{34}$$

where S is the site coefficient for soil characteristics that takes the value of 1.0, 1.2 or 1.5 depending on the soil classes A, B, or C, respectively, described in the Code. While the descriptions of the three soil classes are identical to those given by Eurocode 8, the values assigned to the factor S are, however, significantly different.

The Fundamental Period, T_1

The specifications of EBCS 8 for the computation of the period are essentially the same as those of Eurocode 8.

The Behavior Factor, γ

This factor has the same purpose of accounting for the energy dissipation capacity of the structure, mainly through its ductile behavior, as the factor q of Eurocode 8. The code specifies its values for different materials and structural systems. For concrete structures, it does not exceed the value of 0.70; for steel structures, it ranges from 0.17 to 1; for timber structures, it varies from 0.3 to 1.0 depending on the structural system.

For a bedrock acceleration of α_0=1, common-occupancy structure (I=1), and an elastic response (γ=1), Eq. (32) of the design spectra simplifies to Eq. (34). This equation is plotted in Fig. 4 for the three soil classes. The constant upper bound of 2.5 and the variation of the declining branch according to $T^{-2/3}$ are to be noted.

Vertical Distribution of Seismic Forces

The base shear is distributed in almost the same manner as Eq. (5) specified by UBC and allowed also by Eurocode 8. EBCS 8 deviates from all codes, however, in that it deducts the top force, F_t, from the base shear irrespective of whether the structure is of long or short period. It does not also provide for other fundamental mode shapes than the linear one implied by Eq. (5). A significant improvement is made in this respect by IBC 2000, which allows parabolic and other mode shapes for taller structures (see Eq. (23)).

Story Shear and Story Overturning Moment

EBCS 8 does not provide formulas for the computation of these quantities and does not state how they are distributed among the resisting elements. As the manner of distribution of these quantities is dependent on factors like diaphragm rigidity, torsion and p-delta effects, this issue needs due consideration in the future.

Torsion

The requirements with respect to torsion are essentially the same as those of Eurocode 8.

Story Drift

EBCS 8 – 95 limits the interstory drift, d_r, to a maximum of $0.01h$ for structures with attached nonstructural elements of brittle materials, and to $0.015h$ for structures having nonstructural elements fixed in a way as not to interfere with structural deformations. This is equivalent to assuming a

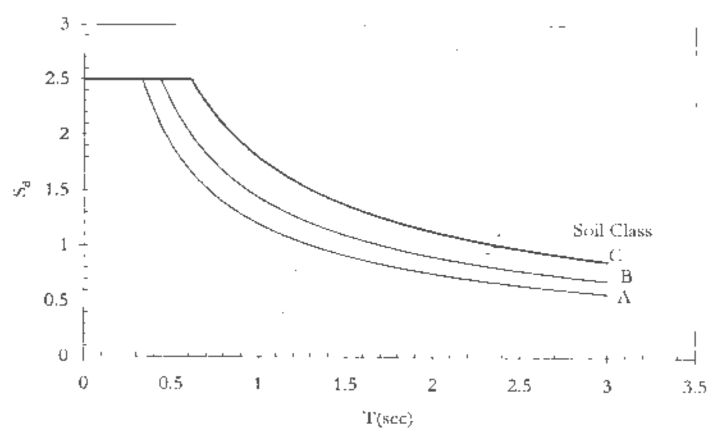

Figure 4: The design spectra of EBCS 8 for the ESF method of analysis for a bedrock acceleration ratio of, $\alpha = 1$, common occupancy structure (I=1), and an elastic response of the structure (γ=1)

value of 2.5 to the reduction factor, μ, employed in Eurocode 8. The displacements, d_s, of the masses for this purpose are calculated from the elastic displacements, d_e, by dividing this by the behavior factor, γ.

***P*-delta Effects**

The requirements with respect to *P*-delta effects are the same as in Eurocode 8 with the sole difference in the upper limit of θ. EBCS 8 limits θ to a maximum of 0.25 instead of 0.30 as specified by Eurocode 8.

CONCLUSIONS

On the basis of the comparative study presented in the previous sections, the following major concluding remarks can be made:

1. A clear disparity exists in the definition of the seismic shear coefficient among the various codes studied. Even within the same code of UBC, the definition in UBC 94 is different from that of UBC 85, and that of UBC 97 is again different from both UBC 94 and UBC 85. A significant change in the definition of the seismic shear coefficient within the UBC series was introduced in UBC 88 and UBC 97. Almost all factors included in the seismic coefficient are modified drastically. The definition of EBCS 8 seems to have closer similarity to that of UBC 94, especially with respect to the zone factors, than to the other codes considered. However, evident deviations exist in the definition of the other factors. Some EBCS 8 provisions share also common features with Eurocode 8.

2. Eurocode 8 definition of the seismic coefficient, termed as the design spectrum in this code, does not neglect the left linear branch, as do all the other codes. It also specifies a smaller upper bound of the seismic coefficient for the softest subsoil class, unlike the other codes, which employ the same upper bound for all kinds of soil profile.

3. EBCS 8 does not provide (but allows) closed form analytical expressions based on structural dynamics theory for the period computation like Rayleigh's quotient, which is provided by other codes like the UBC series. Besides, it does not set an upper bound to the period computed using such analytical methods. In this regard it has similarity with Eurocode 8.

4. While the seismic coefficient in UBC 94, Eurocode 8 and EBCS 8 varies in accordance with $1/T^{2/3}$ in the constant-velocity branch, that of UBC 97 and IBC 2000 varies according to 1/T. The latter is in agreement with the proposed design Spectra of Newmark and Hall [8,9], which is based on statistical analysis of ensembles of response spectra.

5. Only three different soil classes are considered by Eurocode 8 and EBCS 8, while four classes are considered by UBC 94 and six classes by the recent codes of UBC 97 and IBC 2000.

6. The approach towards incorporating site effect in the base shear coefficient showed a drastic change in UBC 97 and IBC 2000. Especially the rationalized approach followed by IBC 2000 marks a milestone in both the quantitative technique of evaluating the soil profile as well as in the manner of incorporation of the site effect on the base shear coefficient.

7. In the vertical distribution of the base shear, EBCS 8 deviates from all the other codes in that it subtracts the top force, F_t, from the base shear irrespective of the magnitude of the fundamental period.

8. IBC 2000 introduced quite a new approach of quantifying seismic hazard of sites. It replaced the classical zoning of regions on the basis of peak bedrock acceleration by the new contour map of spectral accelerations on the surface for short and one-second period. This recent approach has the advantage, among others, of assigning spectra to any site by interpolating between successive contour lines in contrast to the constant value of the zone factor assigned to all sites within a zone in the older zone-based mapping. This approach can heavily influence the approach of seismic hazard mapping to be followed by EBCS in the future.

9. For the distribution of the base shear, IBC 2000 employs a linear mode for structures of short period only (T≤0.5 sec). For all other structures it uses a nonlinear fundamental mode as a basis. All the other codes are based on a linear fundamental mode. This is once

again an important development and more realistic.

10. IBC 2000 uses reduced overturning moments in lower stories of buildings taller than 10 stories. No such reduction is made by the other codes.

11. The requirements and provisions of EBCS 8 with respect to torsion, story drift and P-delta effects are similar to those of Eurocode 8 with some differences in the upper limits of the story drift and the moment ratio. The corresponding regulations of IBC 2000 exhibit, however, a significant difference from both codes and even from UBC 97.

ACKNOWLEDGMENT

The author would like to pass his sincere thanks to Dr. Samuel Kinde of Nanogen Inc., San Diego, California, for he kindly provided a set of invaluable reference material that helped a lot in the compilation of this work. The communication with him was also very encouraging and constructive.

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